Cascading Organizational Change

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Abstract
This article develops a formal theory of the structural aspects of organizational change. It concentrates on changes in an organization's architecture, depicted as a code system. It models the common process whereby an initial architectural change prompts other changes in the organization, generating a cascade of changes that represents the full reorganization. The main argument ties centrality of the organizational unit initiating a change to the total time that the organization spends reorganizing and to the associated opportunity costs. The central theorem holds that the expected deleterious effect of a change in architecture on the mortality hazard increases with viscosity and the intricacy of the organizational design.
(*Organizational Change*; *Cascades*; *Organizational Mortality*)

Introduction
The theory of structural inertia (Hannan and Freeman 1977, 1984) has motivated a considerable body of empirical research on the effects of change in core organizational features on the hazard of mortality.[1] This research generally supports the basic insights of the theory. However, the theory has not developed in parallel with empirical research on these issues. We think that further progress in understanding organizational inertia and change requires sustained attention to theoretical foundations.

This article has two broad objectives. First, we propose a formal language that is suitable for expressing the insights of the original theory and also supporting efforts to deepen and broaden it. Second, we use this language to embed the original arguments in a richer model of organizational structure and to show that some key assumptions of the original theory can be derived as theorems in the new one. This effort involves elaborating what might be called microfoundations for organizational ecology.[2]

At least four types of processes delay—and often prevent—organizational change: (1) structural processes, including the consequences of intricacy and viscosity (sluggishness of response); (2) institutional processes, involving identities and the "moral" character of structural arrangements; (3) political processes, involving interests and interest-group politics; and (4) learning processes, involving feedback over time. While any specific major organizational change likely activates several, or even all, of these processes, we think it clarifies the analytical picture to deal with them separately. This article addresses only some of the basic structural processes; it makes no claim to comprehensiveness.

The original theory of structural inertia pertains to changes in the "core" features of organizations, not peripheral ones. In developing this theory, Hannan and Freeman (1984) provided some specifics—They claimed that four features constitute a generalized core: (1) the organizational mission, (2) the form of authority and the nature of the exchange between the organization and its members, (3) the basic technology used to transform inputs into outputs, and (4) the organization's general marketing strategy. Limiting the scope of the theory in this way—the restriction to a set of purported canonical features—now seems unfounded. Moreover, this limitation on scope does not constrain empirical research: A review of studies testing the main implications of the theory shows that researchers claim a very wide variety of organizational features as among the canonical core features (Barnett and Carroll 1995, Carroll and Hannan 2000).

We advance here a structural alternative to specifying coreness. We examine changes in an organization's architecture (defined as a code system) and analyze their impacts in terms of the cascades of subsequent changes throughout the organization. We follow the original theory in positing that such architectural changes initiate periods of reorganization. We define such reorganization periods precisely in two ways: (1) the total time spent reorganizing in all parts of the organization even if some occur simultaneously and (2) the temporal span required to bring all the organization's feature values in line with the new architecture. We assume that the total time spent reorganizing increases with the intricacy of an organization's design, where intricacy is defined as a strong and

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complex pattern of interconnections among the organization's component units and with viscosity, the typical time it takes for a unit to respond to changes and bring local architecture into conformity.

The second part of the argument ties these considerations to organizational mortality using the standard assumption that an organization's hazard of mortality is proportional to its stock of resources. We assume that reorganization diminishes an organization's ability to take advantage of opportunities. It then follows that organizations undergoing reorganization miss more opportunities relative to those that are not reorganizing, thereby lowering resources and increasing the hazard of mortality. The key theorems hold that the expected effect of organizational change on the mortality hazard increases with the intricacy of design and viscosity.

Formalizing Organizational Ecology

Organizational ecology and demography have spawned a variety of thriving theory fragments and bodies of related empirical research. These include theories of:

- structural inertia and change (Hannan and Freeman 1984, Haveman 1992, Barnett and Carroll 1995, Hannan et al. 2003),
- age dependence (Barron et al. 1994, Sørensen and Stuart 2000),
- niche width (Hannan and Freeman 1977, Dobrev et al. 2001),
- resource partitioning (Carroll 1985, Carroll and Swaminathan 2000, Park and Podolny 2000),
- density dependence (Hannan 1989, Carroll and Hannan 1989, Hannan and Carroll 1992, Barron 1999, Ruef 2002),
- localized competition (Hannan and Freeman 1977, McPherson 1983, Baum and Singh 1994, Podolny et al. 1996),
- organizational identities and forms (Zuckerman 1999, Ruef 2000, McKendrick and Carroll 2001, Baron 2002),
- social movement forms (Minkoff 1999, Ingram and Simons 2000, Olzak and Uhrig 2001, Swaminathan and Wade 2001, Sandell 2001),
- red-queen evolution (Barnett and Hansen 1996, Barnett and Sorenson 2002), and
- recruitment-based competition (Sørensen 2000).

These strands can sensibly be regarded as fragments in a larger research program because they (1) build on a common conception of the organizational world as shaped by processes of selection and (2) share methodological presumptions and practices (Carroll and Hannan 2000). A considerable amount of formalizing activity has already taken place in this arena. Various fragments have been subject to rational reconstruction and logical analysis designed to test the soundness of the arguments. Fragments analyzed in this manner include: structural inertia and change (Péli et al. 1994, 2000), niche width (Péli 1997), and age dependence (Hannan 1998; Pólos and Hannan 2002, 2003). These efforts took seriously the "frozen" published texts; that is, they translated the natural-language renderings of the arguments into a formal language and checked the proofs of the claims in that language. Although this work has been valuable in establishing the soundness of the main arguments and in filling gaps in arguments, it has taken a largely passive role with respect to moving the theories forward. In particular, because these efforts consider each fragment in isolation from the others, they did not clarify the relationships among the fragments.

The relationships among organizational ecology's theory fragments do require clarification. The preponderance of effort over the last 25 years has focused on empirical testing, with relatively little attention paid to issues of theoretical integration. A lack of progress on integration makes it hard to envision exactly which empirical projects would move the larger program forward substantially.

In a pair of previous articles, we began a series of projects aimed at integrating the theory fragments by developing a formal language that allows a precise definition of the key units of organizational ecology: form and population (Pólos et al. 2002) and the niche (Hannan et al. 2003). This article continues the effort by turning to the Hannan-Freeman (1984) theory of structural inertia. We attempt to embed the theory in a richer model of organizational structure such that some of what the original theory assumed can be derived. Moreover, we want to construct this model broadly so that it can also serve as a foundation for other related fragments. We use logic as the modeling tool because it allows us to keep the structure of the argument close to the original formulations and the key intuitions while also establishing the soundness of the arguments. We use a particular nonmonotonic logic that regards the causal claims of the arguments to be rules with exceptions. The Appendix sketches the logic; full details can be found in Pólos and Hannan (2003).

We build models on two levels. We specify processes holding for units in an organization and we derive implications at the organization level. We concentrate on the possibility that actions in one unit can set off cascades of actions in other units. We argue that long cascades complicate organizational action and heighten the risk of failure. Our formal representation of these arguments

Table 1 Notation: Logical Constants, Predicates, Functions, and Relations

Logical Constants	
$\vee$	disjunction
$\wedge$	conjunction
$\neg$	negation
$\exists$	classical existential quantifier
$\forall$	classical universal quantifier
$\rightarrow$	classical material implication
$\mathfrak{N}$	nonmonotonic "normally" quantifier
$\mathfrak{A}$	nonmonotonic "ad-hoc" quantifier
$\mathfrak{P}$	nonmonotonic "presumably" quantifier
Predicates	
$\mathsf{O}(o, p)$	x is an organization in population p
$\mathsf{re}(u, t, t')$	u is in reorganization during $[t, t')$
$\mathsf{RE}(o, t, t')$	none of o's units is in reorganization during $[t, t')$
$\mathsf{u}(u, o)$	u is a unit in organization o
Functions	
$c(u)$	centrality of unit u
I_o	intricacy of organization o
Relations	
$\Vdash$	dominance relation over units

Table 2 Notation (cont'd.): Random Variables, Probabilities, and Key Parameters

Random Variables	
$d(u, t)$	duration of an induced violation in unit u
$D(o, t \mid \delta(u, t) = 1)$	sum of the durations of the induced violations in a cascade initiated by unit u at time t
$D(o, t)$	sum of the durations of the induced violations in a cascade initiated by a random unit at time t
$\delta(u, t) = 1$	unit u initiates an architectural code change just before t (=0 otherwise)
$\Delta(o, t) = 1$	organization o experiences an architectural code just before t (= 0 otherwise)
$m(u, t, t')$	number of opportunities missed by unit u during $[t, t')$
$M(u, t, t')$	number of opportunities missed by org. o during $[t, t')$
$\mu(o, t)$	organization o's hazard of mortality at t
$N(o, t \mid \delta(u, t) = 1)$	number of units with induced violations in o in a cascade initiated by unit u at t
$N(o, t)$	number of units with induced violations in o in a cascade initiated by a randomly chosen unit at t
$R(o, t)$	organization o's stock of resources at t
$v(u, u', t) = 1$	unit u' induces an architectural code violation in u at t (=0 otherwise)
Organization-Specific Parameters	
λ_o	hazard of initiating arch. change for units in o
Λ_o	hazard of initiating arch. change for organization o
π_o	probability of induced arch. code violation for units in o
τ_o	characteristic duration of an induced violation in o (viscosity)
Population-Specific Parameters	
η	probability that a unit misses an opportunity while in not in reorganization
$\tilde{\eta}$	probability that a unit misses an opportunity while in reorganization
Ξ	arrival rate of opportunities for organization o

thus works on two levels. Our notation is complicated by the fact that we specify parallel functions and random variables at the unit and organizational level. To keep this distinction straight, we use the convention that predicates functions, or random variables that are defined for an organizational unit, are expressed in lower-case strings and that those defined for entire organizations are in upper-case strings. Tables 1 and 2 summarize our notation.

It is important to recognize that the arguments pertain to the domain of organizations. Although we intend that our arguments apply generally to organizational worlds, not all kinds of organizations can be compared meaningfully in a straightforward fashion. The fields of organizational demography and ecology make clear that comparisons make the most sense when attention is paid to populations of organizations (Carroll and Hannan 2000). We intend that the theory be understood as applying to all populations of organizations, and we are not aware of any exceptions. If we did know of such exceptional cases, we would express the entire theory as holding as a rule with exceptions, and we would employ nonmonotonic quantification over populations.[3]

Organizational Architecture

Organizational analysts commonly distinguish between architectural (formal) and cultural (informal) features. Consistent with Weber's (1968) early observations on bureaucratic structure, architecture refers to the formal ("official") specifications of an organization and its governance. Architectural choices are reflected in the formal structures for assigning work, that is, construction of the units that undertake the subtransactions. The choices also specify the means of coordinating members and units, monitoring them, and allocating resources and rewards. Culture governs the processes by which work actually gets completed.

When viewed abstractly, specific architectural (and cultural) elements can be regarded as the values of functions that specify organizational features. As Simon (1951) explained in analyzing the employment relation, such feature values are not defined with absolute sharpness; rather they allow a certain amount of tolerance.[4] We posit that architectures discriminate between the allowed and disallowed feature values. That is, they impose constraints on feature values, limiting the values that they can legitimately take.

An appropriate language for expressing architectures ought to be capable of reflecting these considerations. Moreover, it should allow precise judgments about the consistency of the various features that comprise an architecture. We opt for a linguistic formulation. Architectures can be represented as collections of sentences pertaining to ontology (e.g., definitions of the units in an architecture) and rules (e.g., statements of which units have authority over which other units). We regard such sentences as codes. As explained in Pólos et al. (2002), the notion of code can be understood as both (1) a set of specifications in a blueprint, as in the genetic code, and (2) a set of rules of conduct, as in the penal code. Our use of the term code reflects both meanings.

The task of modeling the consequences of violations of architecture is complicated by the fact that the codes differ in importance. Some codes matter greatly in the sense that violations are punished very severely, while others are handled with a lighter touch; consider the distinction between felonies and misdemeanors. Modeling the processes that control the status of codes in this dimension poses numerous challenges, and we do not attempt it here. Instead, we restrict the theory to apply to serious codes. Henceforth, when we refer to architectural codes, we always mean only the serious ones, those for which observable violations bring strong sanctions.

We model an architecture as a set of values on the relevant organizational features (e.g., form of authority, pattern of control relations, accounting principles, compensation policies). Some relevant features are common to units in an organization (e.g., those that pertain to its global architecture); others vary by type of unit. We describe the architecture of a unit by identifying the relevant features and determining the set of alternative values of each feature. For instance, *form of authority* might be a relevant feature; and the alternative values might be bureaucratic, professional, and charismatic. In other words, we consider features to be functions that map from organizations and time points to the range of possible values. We denote the kth feature of unit u at time t as $f_k(u, t)$, and we denote the range of possible values by the set $\mathcal{A}_{k,u,t}$. The space of potential architectures for the unit is the Cartesian product of the sets of possible values taken over all of the relevant features: $\mathcal{A}_{ut} \equiv \mathcal{A}_{1,u,t} \times \mathcal{A}_{2,u,t} \times \cdots \times \mathcal{A}_{K,u,t}$. Finally, we let $\mathbf{a}_{ut}$ denote the unit's actual architecture, the set of choices of values for each of the relevant features.

It will also prove helpful to have a formal representation of the architectural codes. These codes restrict the set of allowable architectures. A sharp architectural code rules out many of the possibilities in $\mathcal{A}_{ut}$; a loose architecture places few constraints on the architectural choices of the unit. It will be important to distinguish architectural codes controlled by the unit from those imposed externally. Let $\alpha_{ut} \subseteq \mathcal{A}_{ut}$ denote the set that contains the allowable architectures for unit u at time t, and α^i_{ut} and α^e_{ut} be the internally and externally controlled subcodes, respectively: $\alpha_{ut} = \alpha^i_{ut} \cup \alpha^e_{ut}$ (for simplicity, we assume that the two subcodes are disjoint). The imposed codes reflect a superordination relation among units; they could arise from specified lines of authority, from the flow of work or from any similar relation that allows one part of the organization to impose constraints on another part. An important class of interunit relations concerns subordination in choice of architecture.

Notation. We use the two-place predicate $\mathsf{O}(o, p)$ to tell that "o is an organization in population p." The predicate $\mathsf{u}(u, o)$ tells that "u is a unit of the entity o, where $\mathsf{O}(o, p)$." We add the background assumption that units belong to only one organization.[5] Let the relation $u \Vdash u'$ indicate that "u and u' are units in the same organization and u is superordinate to unit u' in the sense that choices of architectural feature values by u create architectural code restrictions (binding constraints) for u'." And, let the random variable $\delta(u, t)$ equal one if unit u changes its architecture just after t and equal zero otherwise. When we want to refer to an organization—rather than a unit—undergoing architectural change, we use the random variable $\Delta(o, t)$, which equals one if any unit in organization o experiences architectural change at (just after) time t and equals zero otherwise.

Induced Code Violations and Cascades

The situations that we analyze begin with a change in architectural codes by a particular organizational unit. The initiating unit might sit anywhere in the organization's formal hierarchy. The reasons for this initial change are not pertinent to our theory; they could encompass a wide variety of possibilities including changes in external opportunities and constraints, executive tinkering, and internal strife. The specific change undertaken might be sensible in that it would likely improve organizational alignment and functioning, but we do not assume that this is so—changes surely can also degrade performance. We focus on cases in which the initiating change is architectural because the architecture is more malleable to management and to individual decision makers: Changing the architecture often requires only a directive from someone with authority.

Inconsistencies between new and existing codes normally become salient and consequential when actions that would have satisfied the old code do not satisfy the new code. We represent this situation formally by defining violations of a unit's architectural code that are induced by another unit with the random variable $v(u, u', t)$.

Definition 1. A unit experiences induced violation of new architectural code if and only if an induced change in its architectural code results in its feature values violating an architectural code when no violation existed prior to the change. In formal terms, $v(u, u', t) = 1$ if and only if

(1) $\mathsf{O}(o, p) \wedge \mathsf{u}(u, o)$ and u is subordinate to u';

(2) unit u' initiates an architectural change at time t;

(3) just before the change, unit u's architecture conforms to all of applicable architectural code;

(4) after the change, u's unchanged architecture does not conform to the newly imposed architectural code.

And, $v(u, u', t) = 0$ otherwise.

Organizational changes often generate cascades of related changes in the sense that a single initial change often begets a series of subsequent changes as well. For instance, consider Alfred P. Sloan's (1963, p. 50) description of the architectural change at General Motors in 1920 that implemented its fabled decentralized organizational structure:

> The principles of organization ... thus initiated for the modern General Motors the trend toward a happy medium in industrial organization between the extremes of pure centralization and pure decentralization. The new policy asked that the corporation neither remain as it was, a weak form of organization, nor become a rigid, command form. But the actual forms of organization that were to evolve in the future ... what exactly, for example, would remain a divisional responsibility and what would be coordinated, and what would be policy and what would be administration—could not be deduced by a process of logic from the "Organization Study" [the plan].

Sloan goes on to describe in detail how subsequent specific changes in the likes of product policy, coordination mechanisms, and financial policy were needed to make them consistent with the new basic architectural structure.

Why do such cascades occur? If the code violations arising from an architectural change can be reduced by changing a subset of other codes, or by changing a feature value, then the initial architectural change can be said to induce change in this second set of codes, or in the feature value. Suppose that the process of seeking to remove the code violations created by an architectural change boundedly follows rational search. The agents, having changed one set of elements and experienced violations of the changed codes, search locally to find whether change in any other set of codes or feature values might eliminate the code violations. The search operates locally in the sense that it takes the initial change as given. It follows bounded rationality in the sense that it stops whenever it finds a simple adjustment that eliminates the code violation (even if other, more distant changes might do this as well and also provide some other benefits). Such a search-and-adjustment process can yield a cascade of changes. Each time that the process leads to the decision to implement a set of conforming changes, these new changes play the role of (second-order) changes. They initiate a new local boundedly rational search for ways to eliminate code violations (conditional on the initial change and the second-order changes) by changing yet other elements. At this step, the search process might consider trying to undo the original change. However, it often might be extremely difficult to restore the status quo ex ante, to "put the Genie back in the bottle." This is because the structure of relationships prompting the chain of induced changes may be hierarchical or uni-directional.

The presence of hidden codes provides another possible source of cascades. Architectural codes often take a conditional form: The codes are formulae stating that, if a certain set of conditions holds, then certain other conditions should also hold. Suppose that the antecedent in a conditional code does not obtain. Then the code is satisfied vacuously, whatever the condition on the consequent. Such codes or constraints can be regarded as inactive. If a code has been inactive for a long time, then it likely gets forgotten. In such a case, the code becomes hidden. Now suppose that an architectural change activates the antecedent in a hidden code; then this action might create a new (unforeseen) code violation.

How might cascades of architectural code changes be represented formally? We begin with a code change in a particular unit and trace out the chains of induced changes in subordinate units. We analyze cascades at three levels of detail. The most refined level is an actual cascade initiated by a particular architectural change. At this level of detail, we trace the sequence of impelled changes. At an intermediate level of detail, we analyze the set of possible cascades that might be initiated by a particular initial change. Here we characterize the average properties of the cascades in the set of possibilities. At the least refined level, we consider the average properties of the set of cascades that might result from an initiating event in a random unit. We need this more aggregated characterization to compare changes (and to assess their expected impacts) across organizations without having to specify the exact details of what codes or features values get changed.

Detailed Structure of a Specific Cascade

At the most refined level, we pay attention to the exact sequence of code changes that comprise a cascade.

DEFINITION 2. A particular cascade of resolutions of induced architectural code violations in organization o that begins at time t with a change initiated by unit u is constructed as follows:

Step 0. The unit u, not in violation of any of its applicable architectural code, initiates the cascade at time t by changing architectural code, and that change induces architectural code violations in one or more other units;

Step 1. A unit with an induced violation in Step 0 changes its architecture such that conformity eliminates the induced violation, but this architectural change induces a violation in one or more other units;

Step L. The only unit with an unresolved induced violation (generated by the previous steps in the cascade) eliminates the violation at time t_L, and this architectural change does not induce a violation in any unit.

We denote such a cascade as $\mathbf{K}(u, t)$, where the variables identify the unit that initiated the cascade (u) and the time of initiation (t).

This particular cascade need not be the only cascade that might be initiated by the change in Step 0. At each step, the unit resolving an imposed architectural violation might have a choice among several alternative resolutions. Which one it chooses then determines which other units experience an imposed violation, which shapes the direction of the cascade. Note also that if at any step more than unit other unit is induced, then the initial change has set off a cascade with multiple branches, each of which might possibly be resolved simultaneously.

A cascade can be characterized in terms of its number of stages, the number of units that experience induced violations during the cascade, and its temporal character (including the time elapsed from origin to conclusion and the total time units spent reorganizing even if in parallel). A stage in a cascade is initiated each time that a change by one unit induces violations in one or more other units. A cascade with no indirect effects has only one stage. A cascade in which the adjustments to the first stage induce violations that have no indirect effects has two stages, and so forth. Thus we can measure the number of stages in a cascade in terms of the number of units whose changes induce violations in one or more units.

This detailed account of the structure of a possible cascade highlights the precise connections that animate the cascade. Such a description might be useful for a case study or for close study of a small number of cascades. But it would likely prove too cumbersome as a device for comparing change processes in different organizations (whose code systems likely differ). Therefore, we now strip much of the detail from the story and focus on the most comparable elements of cascades, and we introduce probabilistic considerations explicitly.

Organizational Design and Cascades

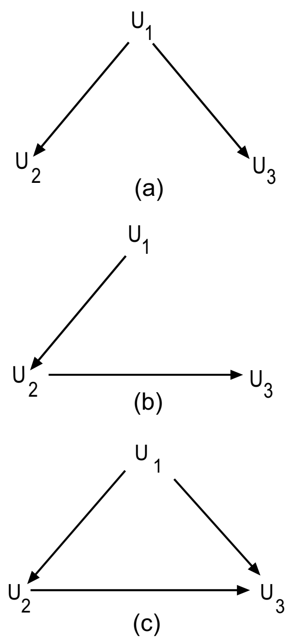
The first step in moving toward a characterization of change that abstracts from the details of the actual code substitutions involves recognizing that an organization's design might affect its possible cascades. The specific design idea that we emphasize is that, generally speaking, organizations with complicated patterns of interconnections among their units will generate longer cascades. This is because a change in any given unit is likely to affect many other units when interconnectedness is complex (Simon 1962).

To formalize this notion, we start by analyzing the pattern of connections among units. These interconnections suggest a variety of possible cascades for any initial architectural change. To derive the cascade that will likely be realized from this set, we make a stochastic assumption about the level of coupling among units in the organization. This framework then allows us to make predictions about certain characteristics of a cascade, including its expected total time spent reorganizing.

Unit Interconnections

Consider the following examples involving three architectures as depicted in Figure 1. Here the directed lines indicate the constraints embedded in the architecture. An arrow directed from u_i to u_j indicates that $u_i \Vdash u_j$. On the left in the figure, Figure 1a, we see a flat hierarchy ("star" network): Unit u_1 directly constrains u_2 and u_3, which are otherwise unconnected. In the middle, Figure 1b, we have a vertical hierarchy. In this case, u_1 constrains u_2 directly and u_3 indirectly. Figure 1c

Figure 1 Illustration of Three Different Patterns of Connections Among Units



depicts a case in which the classic attribute of hierarchy (unity of command—each unit has only one direct superior) is violated. (This case, unlike the others, cannot be described as a lattice.) In this case, u_1 constrains u_2 and u_3 directly and u_2 constrains u_3 directly. Thus u_1 constrains u_3 directly and indirectly.

Consider the likely effect of an architectural change in the dominant unit (u_1) in each case. In Case (a), u_2 and u_3 can act independently in solving the problem, changing local architecture and resolving the violation. Thus there is only one stage in the cascade, and the temporal span of the cascade is simply the maximum of the durations of the unresolved code violations in the two units. In the case of the three-level hierarchy, Case (b), there are two stages in the cascade: one in which u_2 adjusts to the initial change and another in which u_3 adjusts to the induced change in u_2. In this case the temporal span is the sum of the durations of the unresolved code violations in the two units.

Finally, the nonhierarchical case, Case (c), also has two stages. As in Case (a), the temporal span is the maximum of the two durations. However, the resolution time for u_3 will generally be longer in the nonhierarchical case. Consider two scenarios. First, u_3 resolves the inconsistency induced by the change in u_1 before u_2 does. At this point, the duration of the resolution for u_3 is the same as it would have been in the structure in Figure 1b, the vertical hierarchy. But, it still must adapt to the not-yet-completed change in u_2, so its total resolution time will be greater. In the second scenario, u_2 completes its adjustment to the change by u_1 before u_3 does. This means that additional constraints on u_3 get imposed in the midst of its resolution process. We expect that this will complicate the adjustment and lengthen the period of resolution.

These simple cases suggest two lessons for building a model of the process. First, we should attend to the number of stages of a cascade: The total time spent reorganizing and the temporal span of a cascade will generally increase with the number of stages it contains. Second, we should pay attention to the complexity of the pattern of connections among organizational units: The time spent reorganizing within a cascade will generally be longer the more that the pattern departs from simple hierarchy (Simon 1962).

Unit Centrality and Organizational Coupling

The nuances recognized above can be captured by representing the pattern of connections in an organization's architecture with an eigenvector measure of centrality. Such measures have the general form that a unit's centrality in the architecture depends upon the centrality of the units that it constrains. So a unit is central to the extent that it constrains units that are themselves central. Thus, the most central unit in the flat hierarchy is less central than the most central unit in the vertical hierarchy.

Recall that two units are connected in an architectural sense if the feature values of one govern and constrain the architectural codes of the other. In particular, one unit constrains another architecturally if the feature values (and choices allowed by the codes) of the former are imposed as an external constraint (as codes) on the latter. Let U_o be the number of units in the organization. Consider a $U_o \times U_o$ adjacency matrix $\mathbf{R}$ for which $r_{ij} = 1$ if unit i constrains unit j architecturally and equals zero otherwise, that is, if $u_i \Vdash u_j$.

An architectural change by one unit might or might not induce a violation in a subordinate unit. It depends on the details of the codes—both those codes that get replaced and the relational codes among units. Given this situation, it makes sense to construct a probability model, using the probability that a change in one unit induces an architectural code violation in another: $\Pr\{v(u, u', t) = 1\}$. In general, this probability might vary over pairs of units and over time. Differences in typical induction probabilities among organizations arguably correspond with variations in the tightness of coupling. Loosely coupled organizations presumably tend to have lower induction probabilities than do tightly coupled ones (Weick 1976, Manns and March 1978).

At some point in the development of this kind of model, it might prove useful to analyze probability models that allow the induction probabilities to vary in specified ways among dyads. However, at this point we only want to characterize typical situations for sets of organizations. Therefore, we assume that induction probabilities might vary between organizations but not over dyads within organizations over time for an organization. In other words, we assume that each organization has a characteristic induction probability, which is constant for all dyads and all time periods. This assumption has the status of analytical convenience rather than of a claim about the organizational world. As we explain in the Appendix, we refer to the simplifying assumptions that we expect to see relaxed in further developments of the theory as "ad-hoc assumptions" (meaning that they are temporary assumptions fashioned for the argument at hand), and we refer to the real causal claims of the theory as "postulates." In this article, the ad-hoc assumptions concern the probabilistic structure of the change process. We quantify ad-hoc assumptions using $\mathfrak{A}$ (A in a Gothic font), the "ad-hoc" quantifier discussed in the Appendix.

AD-HOC ASSUMPTION 1. *The probability that an architectural change by a unit induces a violation in a subordinate unit does not vary over pairs of units or time points*; *it is an organization-specific constant, which we denote by* π_o.

$$\begin{aligned}\mathfrak{A}o\ \exists \pi_o\ \forall u, u', t[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o)&\\ \wedge (u' \Vdash u \rightarrow \Pr\{v(u,u',t)=1\}=\pi_o)&\\ \wedge (u' \nVdash u \rightarrow \Pr\{v(u,u',t)=1\}=0)].&\end{aligned}$$

(The formula in this assumption embodies the substantive assumption that the probability normally does not differ among dyads in an organization or over time points for an organization, and it also establishes that we label this probability as π_o for organization o.)

To build a representation of the structure of these random cascades, we use a variation of Bonacich's (1987) measure of centrality.[6] Let $c(u)$ be an index of the centrality of unit u.

DEFINITION 3. The vector containing the centralities of the units of organization o is given by:

$$\mathbf{c} = \sum_{k=1}^{\infty} \pi_o^k \mathbf{R}_o^k \boldsymbol{l},$$

where $\boldsymbol{l}$ is a $(N \times 1)$ vector of ones.

It might prove helpful to apply this measure to the three cases illustrated in Figure 1. The matrices that record the $\Vdash$ relations for these cases are

$$\mathbf{R}_a = \begin{pmatrix} 0,1,1 \\ 0,0,0 \\ 0,0,0 \end{pmatrix}; \qquad \mathbf{R}_b = \begin{pmatrix} 0,1,0 \\ 0,0,1 \\ 0,0,0 \end{pmatrix};$$

$$\mathbf{R}_c = \begin{pmatrix} 0,1,1 \\ 0,0,1 \\ 0,0,0 \end{pmatrix}.$$

The squares of these matrices are

$$\mathbf{R}_a^2 = \begin{pmatrix} 0,0,0 \\ 0,0,0 \\ 0,0,0 \end{pmatrix}; \qquad \mathbf{R}_b^2 = \begin{pmatrix} 0,0,1 \\ 0,0,0 \\ 0,0,0 \end{pmatrix};$$

$$\mathbf{R}_c^2 = \begin{pmatrix} 0,0,1 \\ 0,0,0 \\ 0,0,0 \end{pmatrix}.$$

Because $\mathbf{R}^k$ is a matrix of zeros for $k \geq 2$, we can calculate the vector of centrality scores as follows:

$$\mathbf{c}_a = \begin{pmatrix} 2\pi_o \\ 0 \\ 0 \end{pmatrix}; \qquad \mathbf{c}_b = \begin{pmatrix} \pi_o + \pi_o^2 \\ \pi_o \\ 0 \end{pmatrix};$$

$$\mathbf{c}_c = \begin{pmatrix} 2\pi_o + \pi_o^2 \\ \pi_o \\ 0 \end{pmatrix}.$$

It is clear that the centrality scores vary with the architecture. It is also easy to see that the centrality scores also depend upon the number of units. For instance, adding a third subordinate unit to Case (a), but keeping the architecture otherwise unchanged, would increase the centrality of the dominant unit from $2\pi_o$ to $3\pi_o$; adding another vertical link at the bottom of the hierarchy in Case (b) causes the centrality score of the dominant unit to increase from $\pi_o + \pi_o^2$ to $\pi_o + \pi_o^2 + \pi_o^3$, and so forth. In other words, the centrality scores reflect the density and pattern of ties among units as well as the number of units in the organization.

We propose that this characterization provides a useful representation of a random cascade of induced architectural changes. The cascade begins with an architectural change by a unit at a time point. The random cascade induced by this change can be regarded as a realization from the probability model in A.1[7] and the centrality score of the initiating unit. Let $N(o, t \mid \delta(u, t) = 1)$ be a random variable that records the number of induced violations in the cascade $\mathbf{K}(u, t)$.

Definition 4. The number of induced violations in the cascade in organization o initiated by unit u at time t is given by

$$N(o, t \mid \delta(u, t) = 1) \equiv |\langle u', t' \rangle \in \mathbf{K}(u, t)|,$$

where $|\cdot|$ denotes the cardinality of a set, the number of distinct elements it contains.

Our reason for choosing this notion of centrality can now be seen clearly. The centrality score of a unit in architecture gives the expected number of induced violations in a cascade initiated by an architectural change in that unit, according to the probability model. This is the key to our model. Because this relationship plays an important role in the analysis that follows, we make it explicit.

Lemma 1. *The expected number of induced violations in a cascade initiated by an architectural change by a unit equals its centrality in the architecture,* $c(u)$.

$$\mathfrak{P} o, u, u', t[\mathsf{O}(o, p) \wedge \mathsf{u}(u, o) \rightarrow \mathrm{E}\{N(o, t \mid \delta(u, t) = 1)\} = c(u)],$$

where $\mathrm{E}\{\cdot\}$ *denotes the operation of mathematical expectation.*

Proof. In the nonmonotonic logic, establishing a proof involves constructing the most-specific regularity chains that connect the antecedent and the consequent. The regularity chains are constructed from the available definitions, postulates, strict rules, and ad-hoc assumptions. If the most specific of such a regularity chain supports the claim, then the theorem is proven. If among the most-specific regularity chains, some support the claim and others support the counter claim, then no conclusion is warranted—the claim is not a theorem. Therefore, we construct the most-specific regularity chains in sketching each proof.

The expected number of induced violations, $\mathrm{E}\{N(o, t \mid \delta(u, t) = 1)\}$, can be expressed as the sum of the expected number of violations at each path length. That is, $\mathrm{E}\{N(o, t \mid \delta(u, t) = 1)\} = \sum_{k=1}^{\infty} \mathrm{E}\{N^k(u, t)\}$, where $\mathrm{E}\{N^k(u, t)\}$ is the expected number of induced violations at step k of the cascade (that is, at path length k). The joint probability of k inductions along a path, under A.1, is given by π_o^k. Because inductions must follow the subordination relation, $\mathrm{E}\{N^k(u, t)\} = \sum_{u \neq u'} \pi_o^k z_{u,u'}^k$, where $z_{u,u'}^k$ equals the number of distinct k-step paths connecting u and u'. Inspection of the terms in the powers of $\mathbf{R}$ reveals that $z_{u,u'}^k$ is the (u, u') entry in $\mathbf{R}^k$. □

Temporal Aspects of a Cascade

The temporal dimension of a random cascade within an organization matters decisively for possible consequences, as we explain below. We considered two different ways to represent the temporal dimension of cascades. The first defines the *temporal span* of a cascade as the time elapsed from the initiating event to the elimination event that terminates the cascade, as noted above. The second defines the *total time reorganizing* as the sum of the times spent by the individual units in reorganization mode (changing codes and feature values so as to eliminate induced violations). The total time reorganizing is calculated by summing the durations of all of the reorganizations by units affected in a cascade, even if they occur simultaneously, as with the types of changes discussed by Romanelli and Tushman (1994). Both ideas have substantive promise because a protracted period of reorganization presumably complicates organizational action and diverts the attention of at least some members over the whole period—the first idea—and because the disruption caused by reorganization ought to be proportional to the time spent by units (and their members) in working out the consequences of changes—the second idea. Given that we model processes at the unit level, the argument goes more smoothly when we focus on the second concept for the whole organization, total time reorganizing. Nevertheless, we have to bring temporal span back into the picture when we derive implications of cascades of changes across organizations.

Now it might happen that different paths of induced changes affect a unit such that one reorganization (effort to eliminate an induced violation) gets interrupted by another. We must make clear what we assume for such situations. Start with the situation that does not involve interruption. Let $d(u, t)$ denote the random variable that records the duration of an *uninterrupted* spell of reorganization for unit u to eliminate a violation induced at time t. Suppose, next, that a reorganization does get interrupted in the sense that another violation gets induced before the first has been eliminated. What should we expect about the duration of the reorganization for this unit? We think that the normal case is one in which the duration of the overlapping reorganizations lasts (at least) as long as the sum of the two uninterrupted durations. Consider two scenarios. In one, the problem of eliminating the second induction gets postponed until the first reorganization finishes. In the other, some attention gets shifted from the first reorganization to the second. In both cases, the amount of work to be done is arguably the same.[8] We simplify and assume that the expected time elapsed during the two overlapping reorganizations equals the sum of expectations of the durations of the two reorganizations in the uninterrupted case.

Again we opt for simplicity in characterizing the probability model. We assume that an organization's units have a typical expected duration for induced violations, that this expected duration varies among organizations, but not within organizations (over episodes).

Ad-hoc Assumption 2. *The expected unit-level duration of an induced violation of an architectural code does not vary over units or over time*; *it is an organization-specific constant*: τ_o.

$$\mathfrak{A}o\ \exists\tau_o\ \forall u, u', t[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o) \wedge (v(u,u',t)=1) \\ \rightarrow \mathrm{E}\{d(u,t)\} = \tau_o].$$

How should we think about τ_o? A large value of this constant means that it typically takes a long time for a unit to correct induced violations. To use a physical analogy, an organization in which things work slowly has high *viscosity*—think of the difference between stirring honey and water. Viscosity is often defined (loosely) as the resistance in a material to changes in form. Because this analogy seems to fit the organizational context, we will refer to levels of viscosity in comparing organizations with different typical speeds of eliminating induced violations.

The model of a random cascade in A.1–2, coupled with the definition of centrality, yields a substantive insight about the expected total time reorganizing. We express this insight in terms of the random variable, $D(o,t \mid \delta(u,t)=1)$, which gives the number of induced violations in the cascade initiated by unit u at time t.

Definition 5. $D(o,t \mid \delta(u,t)=1)$ is the sum of the durations of all reorganizations triggered by the cascade $\mathbf{K}(u,t)$.

$$D(o,t \mid \delta(u,t)=1) \equiv \sum_{\langle u',t'\rangle \in \mathbf{K}(u,t)} d(u',t').$$

(Note that total time reorganizing is not the same as the temporal span of the cascade; we return to this difference below.)

Theorem 1. *The expected total time reorganizing by an organization during a cascade that originates in unit u is proportional to the centrality of unit u.* (*The constant of proportionality is the organization-specific viscosity.*)

$$\mathfrak{P}o, u, t[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o) \wedge (\delta(u,t)=1) \\ \rightarrow \mathrm{E}\{D(o,t \mid \delta(u,t)=1)\} = \tau_o c(u)].$$

Proof. The most-specific regularity chain uses A.1, A.2, and L.1. □

Comparing Random Cascades: Intricacy and Viscosity

In the foregoing, we considered cascades with specified originating events. This allowed us to characterize the consequences of the originating unit for the kind of cascade that should be expected. We need to make another abstraction so that we can characterize the entire organization in terms of its propensity to generate long cascades. The needed abstraction treats the origin of the cascade as random.

Based on the reasoning used in discussing the alternatives in Figure 1, we propose that the mean centrality score in an organization provides a useful way to express intuitions about likely cascade lengths. A unit has high centrality only if it dominates units that themselves have high centrality. Therefore, cascades are more likely to hit units with high centralization in an organization with a high mean centrality.

Indeed, mean centrality provides a way to characterize the *intricacy* of the organization's design.[9] Let I_o denote a function that records the intricacy of the design of organization o.

Definition 6. The intricacy of an organization's design is equivalent to the mean centrality over its subunits:

$$I_o \equiv (1/U_o) \sum_{u:\mathsf{u}(u,o)} c(u),$$

where $U_o \equiv |\{u \mid \mathsf{u}(u,o)\}|$, the number of units in the organization.

Building a model at the organizational level requires an explicit assumption about the distribution over organizational units of the probability of being the initiator, conditional on a change being initiated. We express this idea in terms of the rate of initiating change. Let $\lambda(u,t)$ and $\Lambda(o,t)$ denote the rates at the unit and organizational level, respectively.

Definition 7. Let $\lambda(u,t)$ denote the hazard of initiating an architectural change in unit u at t:[10]

$$\lambda(u,t) \equiv \lim_{t'\downarrow t} \Pr\{\delta(u,t)=1\}/(t'-t);$$

and let $\Lambda(o,t)$ denote the hazard for organization o:

$$\Lambda(o,t) \equiv \lim_{t'\downarrow t} \Pr\{\Delta(o,t)=1\}/(t'-t) = \sum_{u:\mathsf{u}(u,o)} \lambda(u,t).$$

As with other aspects of the probability model, we go for a high degree of simplicity. We assume homogeneity among units within an organization and over time.

It might seem more natural to assume that the probability of initiating architectural change rises with the level in the organization's hierarchy, that units closer to the top are more likely to initiate changes. This assumption is actually stronger than we need. The general line of argument holds that cascades that start in units with high centrality last longer and therefore create more serious problems.[11]

AD-HOC ASSUMPTION 3. *The rate of initiating an architectural change does not vary over units within an organization or over time for an organization; it is an organization-specific constant*: λ_o.

$$\mathfrak{A}o\ \exists\,\lambda_o\ \forall\,u, u', t, t'\,[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o) \wedge \mathsf{u}(u',o) \rightarrow \lambda(u,t) = \lambda(u',t') = \lambda_o].$$

In developing proofs, we will encounter expressions for the probability that a particular unit initiates a change, given that some unit in the organization initiated a change. Therefore, it is useful to record a straightforward consequence of A.3.

LEMMA 2. *The probability that any chosen unit is the one that initiated a change (when one unit in the organization did initiate a change) equals* $1/U_o$, *where* U_o *is the number of units.*

$$\mathfrak{P}o, u, t[O(o,p) \wedge \mathsf{u}(u,o) \rightarrow \Pr\{\delta(u,t) = 1 \mid \Delta(o,t) = 1\} = 1/U_o].$$

PROOF. This result follows from standard calculations in probability theory. It is easy to show that

$$\Pr\{\delta(u,t) = 1 \mid \Delta(o,t) = 1\} = \lambda(u,t)/\Lambda(o,t).$$

(Just sum both sides over all the units in the organization, and note the second equality in the second line in D.7.) Given A.3 and D.7, the right-hand side of the foregoing formula can be written as $\lambda_o/(\lambda_o U_o) = 1/U_o$. □

In the analysis that follows, we repeatedly calculate expectations of functions of random cascades. These functions involve summations over all of the induced violations in a cascade. In the standard case, in which the size of the set of elements in the summation is deterministic, the calculation uses the straightforward rule that the expectation of a sum of functions of random variables is the sum of the expectations. In the case of cascades, the number of elements in the summation is itself a random variable, $N(o, t \mid \delta(u,t) = 1)$, if the cascade initiates in unit u. Recall also, that $\mathrm{E}\{N(o, t \mid \delta(u,t) = 1)\} = c(u)$, according to L.1. Now consider the case in which the initiating unit is chosen at random (as specified in the ad-hoc assumptions). Let the random variables characterizing a cascade with random origin be expressed as the unconditional versions of the parallel terms for the cascade with known origins. That is, let the number of induced violations in a cascade with random origin be denoted by $N(o,t)$, the total amount of reorganization time in such a cascade as $D(o,t)$, and the temporal span by $T(o,t)$.

LEMMA 3. *The expected number of induced violations within a cascade with a random origin,* $N(o,t)$, *equals the levels of intricacy,* I_o.

$$\mathfrak{P}o, u, t[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o) \wedge (\Delta(o,t) = 1) \rightarrow \mathrm{E}\{N(o,t)\} = I_o].$$

PROOF. According to the law of total probability[12] (and given the premise that a change did occur at t),

$$\mathrm{E}\{N(o,t)\} = \sum_{u:\,\mathsf{u}(u,o)} \mathrm{E}\{N(u, t \mid \delta(u,t) = 1)\} \cdot \Pr\{\delta(u,t) = 1\}.$$

Given A.3 and L.3, the right-hand side of this equation can be rewritten as:

$$(1/U_o) \sum_{u:\,\mathsf{u}(u,o)} \mathrm{E}\{N(u, t \mid \delta(u,t) = 1)\}.$$

According to L.2, this expression reduces to $(1/U_o) \cdot \{\sum_{u:\,\mathsf{u}(u,o)} c(u)\}$, which, by D.6, equals I_o. □

With this result, it is straightforward to derive the expected total time reorganizing in a cascade with random initiation.

THEOREM 2. *The expected total time reorganizing for a cascade with a random origin within an organization is given by the product of the organization's level of intricacy,* I_o, *and viscosity,* τ_o.

$$\mathfrak{P}o, t[\mathsf{O}(o,p) \wedge (\Delta(o,t) = 1) \rightarrow \mathrm{E}\{D(o,t)\} = \tau_o I_o].$$

PROOF. The most-specific regularity chain uses A.2 and L.3. □

Missed Opportunities

We focus on periods of reorganization because devoting attention, time, and energy to reorganization (adjusting codes to eliminate incompatibilities) diverts members of an organization from the tasks that generate revenues. Therefore, any lengthy change process generally entails substantial opportunity costs. Because management attention gets focused on the change, opportunities are foregone, production gets disrupted, relations with customers are left unattended as responsibilities are reallocated, and so forth. Each of these problems becomes more serious as a reorganization lengthens. During a reorganization period, considerable attention is paid to the fate of the new architecture. The units whose architectural codes are altered generally face scrutiny such that nonconformity of feature values to the newly added code gets noted. In other words, unlike the situation of normal functioning in which managerial attention to architectural conformity is partial and episodic, violations of newly added code generally get noticed during a reorganization period. The resulting diversion of attention causes opportunities to be missed.

We specify the consequences of missed opportunities in terms of the growth rate of resources. Let $R(o,t)$ denote the random variable that records the level of o's resources at time t. Organizations lose resources during periods of reorganization, both because reorganization is costly and also because directing resources and attention away from "production" causes a drop in revenue (the acquisition of new resources). For instance, before the spin-off at Agilent Technologies, the CEO of the parent company (Hewlett Packard) warned that the units involved needed to "keep the plane flying" during the reorganization. His comment refers to a tendency in early aviation for pilots and copilots to get obsessed with fixing the "problem" when cockpit lights and buzzers went off and forget about actually flying the plane, thereby causing tragic accidents.

Tying structural change to missed opportunities requires a specification of the flow of opportunities and of the probability of missing an opportunity. We want to continue to specify the basic process at the unit level, but there is a slight complication. Two otherwise similar organizations might structure themselves into different numbers of units. Simply creating more units ought not, by itself, increase the flow of opportunities. Therefore it makes sense to specify that similar organizations in a population experience the same flow of opportunities and that these opportunities are experienced by units in way that reflects the degree of division of the organization into units.

Definition 8. Let the arrival rate of opportunities to unit u at time t be denoted by $\xi(u,t)$ and the arrival rate of opportunities to organization o at time t by $\Xi(o,t)$; therefore, the expected flow of opportunities over a period for a unit equals $\int_t^{t'} \xi(u,s)\,ds$, and for an organization it equals $\int_t^{t'} \Xi(o,s)\,ds$.

Ad-hoc Assumption 4. *The arrival rate of opportunities to a unit in an organization is directly proportional to the arrival rate for the organizational and inversely proportional to the number of units.*

$$\mathfrak{A}o,u,u',t[\mathsf{O}(o,p)\wedge \mathsf{u}(u,o)\wedge \mathsf{u}(u',o) \wedge (|\{u'\colon \mathsf{u}(u',o)\}| = U_o) \rightarrow \xi(u,t) = \Xi(o,t)/U_o].$$

We want to be able to compare cascades that take place at different times for different organizations. Such comparisons are simplest when the process that generates opportunities is stationary. If the arrival rate of opportunities is constant over the period being considered, then we expect similar flows for different organizations over equal-length intervals located at different points within the period. Given this motivation, we add the ad-hoc assumption of stationarity in the arrival process.

Ad-hoc Assumption 5. *Opportunities arrive at the same constant rate for all organizations in a population with the same initial resource level.*

$$\mathfrak{A}o,o',t,t'[\mathsf{O}(o,p)\wedge \mathsf{O}(o',p)\wedge (R(o,t)=R(o',t')) \rightarrow \Xi(o,t)=\Xi(o',t')=\Xi].$$

It is helpful in expressing the assumption that reorganization impedes the exploitation of opportunities to use two predicates: $\mathsf{re}(u,t,t')$, which reads as "unit u is reorganizing during the interval $[t,t')$"[13] and $\mathsf{RE}(o,t,t')$, which reads as "none of the units in organization o is reorganizing during the interval $[t,t')$." Let $q(u,t)$ denote the random variable that equals one if unit u misses an opportunity that arises at time t and equal zero otherwise. The key substantive idea is that reorganization elevates the probability of missing opportunities.

Postulate 1. A unit's probability of missing an arriving opportunity is higher when it is in reorganization.

$$\mathfrak{N}o,o',u,u',t,t'[\mathsf{O}(o,p)\wedge \mathsf{O}(o',p)\wedge \mathsf{u}(u,o)\wedge \mathsf{u}(u',o') \rightarrow (\Pr\{q(u,t)=1\mid \mathsf{re}(u,t)\} > \Pr\{q(u',t')=1\mid \neg\mathsf{re}(u',t')\})].$$

Again we simplify the probability model. Because we want to compare different organizations facing the same opportunity structure and we have assumed that this opportunity structure is common to all members of a population, we assume that the probability of missing opportunities (in reorganization or outside of reorganization) does not vary among units in organizations in the population or over time.

AD-HOC ASSUMPTION 6. *The probabilities of missing an opportunity conditional on reorganization and the absence of reorganization vary over time but not among units in the organizations in a population.*

$$\begin{aligned}&\mathfrak{A}o, o', u, u', t, t' \exists \tilde{\zeta},\\ &\quad \zeta[\mathsf{O}(o,p) \wedge \mathsf{O}(o',p) \wedge \mathsf{u}(u,o) \wedge \mathsf{u}(u',o')\\ &\qquad \to (\Pr\{q(u,t)=1 \mid \neg \mathsf{re}(u,t)\}\\ &\qquad\quad = \Pr\{q(u',t')=1 \mid \neg \mathsf{re}(u,t')\} = \eta)\\ &\qquad\quad \wedge (\Pr\{q(u,t)=1 \mid \mathsf{re}(u,t)\}\\ &\qquad\quad = \Pr\{q(u',t')=1 \mid \mathsf{re}(u,t')\} = \eta + \tilde{\eta})].\end{aligned}$$

As an obvious consequence of P.1 and A.6, we have:

LEMMA 4.

$$\mathfrak{P}o[\mathsf{O}(o,p) \to \tilde{\zeta} > 0].$$

We want to focus on the expected difference in the number of opportunities missed over an interval for a reorganizing unit and an otherwise identical not-reorganizing one. Let the random variable $m(u, t, t')$ give the number of opportunities missed by unit u during the interval $[t, t')$, and let the organization-level counterpart be $M(o, t, t') \equiv \sum_{u:\,\mathsf{u}(u,o)} m(u, t, t')$. We want to characterize the expected value of $m(u, t, t')$. We consider only the simple case that pertains to a complete duration of an induced violation.

LEMMA 5.

$$\begin{aligned}&\mathfrak{P}o, u, u', t_1, t_2, t_3, t_4\\ &\quad \cdot \Big[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o) \wedge \mathsf{u}(u',o)\\ &\qquad \wedge \forall w\big[(t_1 \le w < t_2) \to \mathsf{re}(u,w)\big]\\ &\qquad \wedge \forall w'\big[(t_3 \le w' < t_4) \to \neg\mathsf{re}(u',w')\big]\\ &\qquad \to \big(\mathrm{E}\{m(u,t_1,t_2)\} = \xi_o(\eta + \tilde{\eta})(t_2 - t_1)\big)\\ &\qquad \wedge \big(\mathrm{E}\{m(u',t_3,t_4)\} = \xi_o \eta (t_4 - t_3)\big)\Big].\end{aligned}$$

PROOF. The most-specific regularity chain uses A.4–6. □

Suppose that we set $t_3 = t_1$ and $t_4 = t_2$ in L.5 (the lemma does not claim that they are different). Then we see that the expected excess of missed opportunities for the reorganizer is $\xi_o \tilde{\eta}(t_2 - t_1)$.

Next we want to extend the result to apply to a full cascade of changes for an organization.

THEOREM 3. *The expected number of opportunities missed due to reorganization for an organization during a full cascade of reorganizations increases monotonically with the product of the organization's viscosity, τ_o, and intricacy, I_o.*

$$\begin{aligned}&\mathfrak{P}o, u, t[\mathsf{O}(o,p) \wedge \mathsf{u}(u,o) \wedge (\Delta(o,t)=1)\\ &\qquad \to \mathrm{E}\{M(o,t,t+T(o,t))\}\\ &\qquad = \Xi(\eta T(o,t) + \xi_0 \tilde{\eta} \tau_o I_o)].\end{aligned}$$

PROOF. The most-specific regularity chain uses L.4 and L.5. According to L.5, each unit contributes $\xi_o \eta S(o,t)$, the baseline that holds whether or not a unit is in reorganization. This part of the process therefore contributes $\xi_o \eta S(o,t) U_o = \Xi \eta S(o,t)$ expected missed opportunities. Next consider the additional expected missed opportunities due to reorganization. The expected total time spent reorganizing in a complete cascade equals $\tau_o I_o$ according to T.2. L.5 tells that the expected additional missed opportunities because of reorganization over all of the time spent reorganizing by units is $\xi_o \tilde{\eta} \tau_o I_o$. □

We can use this theorem to compare what happens to two organizations that experience cascades of change. A subtle issue needs attention. The two cascades might differ in temporal scope, S. We want to compare experiences over the time span of the longer cascade, so that we get the full scope of both cascades. Things get very complicated if we allow the possibility that the organization with the shorter cascade starts another cascade within the period of comparison. So we want to restrict the comparison to the case in which no subsequent initiations of cascades occur within the period of comparison.

Notation. To avoid repeating a very complicated expression in a series of lemmas and theorems, we introduce some notational shorthand.

(1) $Z = \max(S(o,t), S(o',t'))$.

(2) The formula Ψ stands for the following formula: the entities being compared, o and o', are organizations in the same population with equal resources, experience architectural changes at times t and t', respectively, and neither experiences another (uninduced) architectural change until the end of the longer of the two cascades of change.

$$\begin{aligned}\Psi \leftrightarrow\ &\mathsf{O}(o,p) \wedge \mathsf{O}(o',p) \wedge \big(\Delta(o,t) = \Delta(o',t') = 1\big)\\ &\wedge (R(o,t) = R(o',t'))\\ &\wedge \forall s, s'\big[(t < s \le (t+Z)) \wedge (t' < s' \le (t'+Z))\\ &\qquad \to \Delta(o,s) = \Delta(o',s') = 0\big].\end{aligned}$$

Application of T.3 for a pair of organizations undergoing cascades shows the role of intricacy and viscosity.

COROLLARY 1. *The difference in the expected number of missed opportunities for two organizations undergoing cascades of change is proportional to the difference in the products of viscosity and intricacy.*

$$\mathfrak{P}o, o', t, t'\big[\Psi \rightarrow \mathrm{E}\{M(o, t, (t+Z)) - M(o', t', (t'+Z))\} = \tilde{\zeta}(\tau_o I_o - \tau_{o'} I_{o'})\big].$$

We focus on missed opportunities because failing to capitalize on opportunities generally lowers the growth in resources. We do not assume any knowledge of the function that relates missed opportunities to the growth in resources; instead, we argue for a weaker monotonicity relationship. (This choice affects what follows: Instead of getting precise results about expectations, we get monotonicity statements relating intricacy, opacity, and asperity to resource growth and mortality hazards.)

POSTULATE 2. Consider a pair of organizations in the same population with equal stocks of resources at the start of a time interval. If one misses more opportunities over the interval than the other, then its expected growth in resources is lower. Otherwise, the expected growth in resources for the two is the same.[14]

$$\mathfrak{N}o, o', t, t', w, w'\big[\mathsf{O}(o, p) \wedge \mathsf{O}(o', p) \wedge (R(o, t) = R(o', t')) \wedge (M(o, t, w) > M(o', t', w')) \rightarrow \mathrm{E}\{R(o, w)\} < \mathrm{E}\{R(o, w')\}\big].$$

Turning back to our example of the architectural decentralization in General Motors, one might naturally wonder how the company managed to survive, even dominate, if these theoretical claims are accurate. After all, the structural change and associated cascade introduced in 1920 should have caused the firm to miss opportunities. Sloan (1963, p. 50) suggests an answer:

> Even mistakes played a large part in the actual events ... and if our competitors—Mr. Ford among them—had not made some of their own of considerable magnitude, and if we had not reversed certain of ours, the position of General Motors would be different from what it is today.

It is reasonable to think the "mistakes" Sloan refers to are the organization's recognition of induced code violations and subsequent adjustments. We interpret his statement as recognizing that adjustments costs were significant and would have damaged the company severely if its competitors had not been experiencing similar difficulties. Given the massive expansion of the automobile market at the time, it seems plausible that the main competitors were all suffering from reorganization pains.

LEMMA 6. *An organization's expected growth rate in resources during a cascade with a random origin decreases with the organization's total time reorganizing, $D(o, t)$.*

$$\mathfrak{N}o, o', t, t'\big[\Psi \wedge (D(o, t) > D(o', t')) \rightarrow \mathrm{E}\{R(o, t+Z)\} < \mathrm{E}\{R(o', t'+Z)\}\big].$$

PROOF. The most-specific regularity chain uses L.5 and P.2. □

Change and Organizational Mortality

Hannan and Freeman's (1984) theory of structural inertia implies that the hazard of mortality rises monotonically with the duration of the period of reorganization. We now show that this implication follows from the new theory posited above. Modern work on organizational mortality analyzes the *hazard* (Carroll and Hannan 2000). Let $\mu(o, t)$ denote the mortality hazard for organization o at time t. Nearly all treatments of the relationship of size and resources with mortality assume that organizations with access to greater resources can better withstand life-threatening environmental shocks (Carroll and Hannan 2000).

POSTULATE 3. If one of a pair of organizations in a population has a higher level of resources than the other, then it has a lower hazard of mortality.

$$\mathfrak{N}o, o', t, t'\big[\mathsf{O}(o, p) \wedge \mathsf{O}(o', p) \wedge (R(o, t) > R(o', t')) \rightarrow \mu(o, t) < \mu(o', t')\big].$$

The most obvious implication of the overall argument is that longer cascades pose higher mortality risks.

THEOREM 4. *The increase in the hazard of mortality due to an architectural change grows monotonically with the time spent reorganizing within the cascade of induced changes.*

$$\mathfrak{P}o, o', t, t'\left[\Psi \wedge (D(o, t) > D(o', t')) \rightarrow \int_t^{t+Z} \mu(o, s)\, ds > \int_{t'}^{t'+Z} \mu(o', s)\, ds\right].$$

PROOF. The most-specific relevant regularity chain uses L.6 and P.3. □

Hannan and Freeman's (1984) key Assumption 9 can now be derived as a theorem.

THEOREM 5. *An organization's hazard of mortality presumably rises monotonically over a period of reorganization.*

$$\mathfrak{P}o, t, s, s'[\mathsf{O}(o, p) \wedge (\Delta(o, t) = 1) \wedge (t < s < s' \leq (t + T(o, t))) \rightarrow (\mu(o, t + s) < \mu(o, t + s'))].$$

PROOF. In the most-specific regularity chain, L.6 holds that stocks of resources decline monotonically with the duration of reorganization, and P.3 states that the hazard of mortality falls monotonically with resources. □

The main line of argument identifies conditions that increase the expected durations of cascades. If stocks of resources fall monotonically during cascades, then the factors that length cascades make change more risky. We want to provide a formal statement of these implications for pairs of organizations that experience random architectural changes and differ in the structural factors that affect expected cascade length. The theorem subsumes a version of Hannan and Freeman's (1984, p. 162) Theorem 5: "Complexity increases the risk of death due to reorganization."

THEOREM 6. *The increase in the hazard of mortality due to an architectural change grows monotonically with the product of intricacy, I_o, and viscosity, τ_o.*

$$\mathfrak{P}o, o', t, t'\left[\Psi \wedge (\tau_o I_o > \tau_{o'} I_{o'}) \rightarrow \int_t^{t+Z} \mu(o, s)\, ds > \int_{t'}^{t'+Z} \mu(o', s)\, ds\right].$$

PROOF. The most-specific regularity chain (given the ad-hoc assumptions) begins with the intension of $\tau_o I_o > \tau_{o'} I_{o'}$. T.4 ties this condition to the expected length of a reorganization period; T.5 completes the chain. □

Conclusion

We have embarked on a series of projects attempting to build new theoretical foundations for organizational ecology. We hope that these efforts will deepen particular theoretical fragments and that the foundations will allow a level of theoretical unification not yet achieved in organizational theory. Our primary goal in this article was to elaborate the structural elements of Hannan and Freeman's (1984) theory of inertia. Structural imagery in the original theory consists mainly of four types of features depicted as constituting the core of the organization, including mission, form of authority, technology, and marketing strategy. The theory assumes that significant or major organizational change involves changing a core feature. It predicts that an organization will encounter resistance if it attempts to change core features; it also implies that changes in core features likely have detrimental consequences. This conceptual approach to structure now strikes us as ad hoc and underdeveloped. We also think that the list of core features does not provide sufficient guidance for empirical research.

Our efforts here advanced an alternative way of identifying the significance of organizational changes. We assessed changes in light of connections in an organization's architecture, defined as a code system. In this framework, a change is significant if it (1) creates violations of architectural codes and (2) the effort to resolve the violations triggers cascades of other changes. We followed the original theory in concentrating on changes directed at architecture and in positing that architectural changes initiate cascades that more fully define periods of reorganization. We defined such reorganization periods precisely as the time its takes to resolve the code violations induced by the initial change. We then tied these considerations to organizational mortality using the standard assumption that the hazard of mortality is proportional to an organization's stock of resources. We assumed that reorganizing diminishes an organization's ability to mobilize resources. If so, then organizations undergoing reorganization lose resources relative to otherwise similar organizations that are not reorganizing. Therefore, reorganization increases the hazard of mortality. The key theoretical finding holds that the mortality risk of an organization increases with intricacy and viscosity.

It makes sense at this point to ask what, if any, implications of the revised theory differ from the original. One way to answer this question is to assess the likely "coreness" of the four original core features in terms of architectural significance, as defined here. If we have made progress, then we would expect to find that there are some interesting differences but that many of the original insights have been preserved. In the relevant passage of the original, Hannan and Freeman (1984, p. 156) argue as follows:

> From the perspective of resource acquisition, the core aspects of organization are (1) its stated *goals*—the bases on which legitimacy and other resources are mobilized; (2) *forms of authority* within the organization and the basis of exchange between members and the organization; (3) *core technology,* especially as encoded in capital investment, infrastructure, and the skills of members; and (4) *marketing strategy* in a broad sense—the kinds of clients (or customers) to which the organization orients its production and the ways it attracts resources

> from the environment. The four characteristics stand in a rough hierarchy, with publicly stated goals subject to the strongest constraints and marketing strategy the weakest ... These four properties provide a possible basis on which to classify organizations into forms for ecological analysis. An organization's initial configuration on these four dimensions commits it to a certain form of environmental dependence and a long-term strategy. ... Although organizations sometimes manage to change positions on these dimensions, such changes are both rare and seem to subject an organization to greatly increased risks of death ... We think that properties of organization charts and patterns of specific exchanges with the actors in the environment are more plastic than the core set ... They can be transformed because attempts at changing them involve relatively little moral and political opposition within the organization and do not raise fundamental questions about the nature of the organization.

Several differences between this initial formulation and that presented here deserve note. First, they employ different bases for establishing coreness. The original argument built explicitly on the notion that organizational forms and populations reflect discontinuities in resource dependencies. The four core features were chosen because of their presumed significance for resource acquisition. Our revised theory builds on the notion that forms and populations are social identities that can be expressed in terms of social and cultural codes (Pólos et al. 2002). Having recognized this difference, it is interesting to note that notions of identity did nonetheless play a part in shaping the original argument. (This facet of the argument has largely been forgotten in contemporary renderings.) Note the emphasis on the "fundamental questions about the nature of the organization."

In particular, Hannan and Freeman (1984, pp. 155–156) motivated the argument about the hierarchy of inertial forces with the example of the university. They pointed out that some features, such as the textbooks used for instruction, change constantly in an adaptive way. However, they argued that changing a curriculum from one based on liberal arts for one premised on vocational training would be extraordinarily difficult. After noting some of the difficulties, they summarized the case as follows (Hannan and Freeman 1984, p. 156):

> The curriculum is difficult to change, then, because it represents the core of the university's organizational identity and underlies the distribution of resources across the organization. In these ways, it can be said to lie at the university's "core."

In retrospect, this view seems more useful for building theory and guiding research than reliance on the quartet of features that have figured more prominently in received empirical research built on the initial theory.

A second difference concerns the role of architecture. The original argument treated architecture as "plastic" and relatively insignificant for understanding inertia and change. Our revised theory allows for the possibility that architectural change might be highly significant. In providing a list of features constituting the core, the original theory did not allow any exceptions, and it did not provide any guidance for dealing with them if they are encountered. In these respects, we believe that the new theory improves the analysis.

The new theory also provides different, specific advice for conducting empirical research on structural inertia. Rather than look at a single type of change in a population of organizations (such that each experiences change as a single time-varying independent variable), the theory implies that the subsequent cascading changes and their temporal dimensions should be studied as well. In current empirical studies, a commonly observed pattern suggests that mortality hazards jump when changes get undertaken, but that they then decline with the time elapsed from the change. On the basis of the new theory, it now seems important to know if the studied structural change is the initiating change in a cascade or simply one episode in a longer sequence. But how much does this matter?

The typical contemporary study traces the mortality consequences through a complete organizational population for a single type of structural change, say a basic product design change among bicycle manufacturers (see Carroll and Hannan 2000 for a review). Although this design represents a definite advancement over previous studies with outcome-biased samples, it does not observe the cascades of changes brought on by the initial adjustment. As a result, none of the following are visible: The total time reorganizing, the temporal span of the cascade, or the end of the period of reorganization. This means that commonly estimated duration effects about the shape of the hazard following a change, based simply on time elapsed since the initial change, may be biased. To see the impact of this, assume for the moment (for ease of interpretation) that the studied change is the initiating event and that there is a positive relation between total time reorganizing and the temporal span of a cascade. Under these assumptions, Theorem 5 implies that the hazard of mortality rises with the duration of the reorganization. But, empirical studies, which have not sought to disentangle reorganization effects from processes that operate after reorganization generally find that the hazard falls monotonically following the initial jump at the time of the change. We suggest that this common pattern might arise solely from the design of these studies. A design that records subsequent changes and better measures the temporal aspects of reorganizing might very well yield different findings.

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Appendix. Theoretical Methodology

The Formal Language

In formalizing our argument we use a language that combines elements of some formal languages routinely used in mathematics and a formal language presented in Pólos and Hannan (2003) to represent the nonmonotonic argumentation in theory building. Some basic mathematical disciplines such as linear algebra, calculus, and probability theory function as meta-theory for this paper. Concepts, language, and insights from these disciplines are used freely.

The logical component of our formal language can be best characterized by the fact that there are four different quantifiers in the language: We have the classical universal quantifier $\forall$ and three nonclassical quantifiers: $\mathfrak{N}$, $\mathfrak{P}$, and $\mathfrak{A}$. These new quantifiers are used to express causal stories, rules with possible exceptions, ($\mathfrak{N}$), presumptions or derived implications ($\mathfrak{P}$), and ad-hoc assumptions ($\mathfrak{A}$). The ad-hoc assumptions are not part of the substantive theory; they are assumptions that allow certain conclusions to be derived from the main postulates. Like the causal stories, the ad-hoc assumptions, also allow for possible exceptions.

As a theory is being built, it is in flux. This means that the theory is partial in several ways. First, the theory is not categorical, i.e., there are classical sentences of the language of the theory that are neither true nor false according to the still-developing theory. Theory building in this respect involves efforts to eliminate the "unknown" truth-values and to replace them with either "true" or "false." Second, the rules or causal stories are generic sentences, rules with exceptions, rather than universally quantified sentences. Third, a theory in flux might not contain all of the relevant rules, and some stages of a theory in flux might contain more rules than others. In this last case, theory building yields extensions of the rule set.

Because of these forms of partiality, the logic of the argumentation has a nonmonotonic character. In logic, monotonicity means that adding premises to an argument cannot overthrow implications that hold for the simpler premise set. If an argument is nonmonotonic, then adding (more specific) premises can eliminate implications of the prior set of premises. Theory building tends to follow nonmonotonic patterns in that better informed stages of the same theory in flux might not support implications that were justified in less well informed stages of the same theory.

We mark the sentences that are responsible for this nonmonotonic behavior with the nonclassical quantifiers. Explanatory principles are the key substantive ingredients of theory, the specific causal explanations. So we call them causal stories. Causal stories differ from classical first-order (universal) principles in two ways. First, causal stories are more stable than classical principles, which get overturned by a single counterexample. Specifically, causal stories should be treated as informationally stable: They ought not be withdrawn even when their first-order consequences get falsified. Instead, the effects of the causal stories are controlled by more specific arguments. Second, the grammatical surface of a causal story typically takes the form of what linguists call bare plural sentences. The normal interpretation of such linguistic forms is as generic sentences (Carlson and Pelletier 1995), which express general—but not universal—ideas. The truth conditions of a generic sentence cannot be expressed in terms of particular cases. In other words, causal stories are default rules that tell what ought to be expected under normal conditions.

As a theory develops, the only thing that can happen to a causal story is that new insights might restrict its domain of application, in the case that knowledge about exceptions develops. Even new knowledge should not lead us to discard a causal story. Instead, we add new rules to the body of knowledge; and we allow the new, more specific rules to override older, more general rules. Suppose that new knowledge casts serious doubt on a causal story. Then discarding it might be exactly the right thing to do. Yet, doing so means that the theory is changed so fundamentally that we should regard the old theory as having been ended and a new theory begun.

Sentences prefixed with the quantifier $\mathfrak{N}$, state what is expected to be the case "normally" according to a causal story. Such sentences yield nonmonotonicity by their inferential behavior. Although rules with exceptions breed nonmonotonicity, once a rule becomes part of a theory in flux it remains part of the theory in any future stages. The implications of these rules might come and go as the theory develops, but the causal stories are not erased.

To mark the sentences that can be erased occasionally by theory development (the implications of rules with exceptions) we use the quantifier $\mathfrak{P}$. Because causal stories are default rules, implications are drawn from them on the basis of the best available evidence. In other words, they are defeasible. Different stages of the theory in flux select different sets of evidence as the best available evidence. However, the defeasible consequences (the presumptions) do not become part of the theory. That status is preserved for the persistent sentences.

Some theory builders assume that the use of mathematical models is the core of formalization. Although we use parts of mathematics (as indicated above), we intend to formalize the argumentation in theory building too. As we argued above, the logic that is suitable for this task is a nonmonotonic logic (see the next section of the Appendix). However, the logic of mathematical reasoning is typically classical first-order logic. To combine these two types of formalism, we need an interface. The interface will be a nonsubstantive ad-hoc assumption. We use the $\mathfrak{A}$ quantifier to mark the ad-hoc assumptions.

Probabilistic arguments often yield expected value differences for some random variables while the causal stories connect the differences of factual values of the same variables to certain outcomes. Suppose that a theory stage implies that the expected value of a random variable for one entity is larger than for another: $\mathrm{E}\{Y(a)\} > \mathrm{E}\{Y(b)\}$. In this case we argue that the same theory stage should be held to presume that a normal outcome is that $Y(a) > Y(b)$. This consideration yields the following assumption schema:

$$\mathfrak{A}a, b[\mathrm{E}\{Y(a)\} > \mathrm{E}\{Y(b)\} \rightarrow Y(a) > Y(b)].$$

We call this formula an assumption schema because one can substitute any random variable for Y and any number of variable (equally long) sequences for a and b and the resulting formula will be an acceptable ad-hoc assumption. It is easy to see that these formulae are not causal stories; they are premises that we find rational to use.

Ad-hoc assumptions sit halfway between substantive assumptions (causal stories) and implications (presumptions). They are assumptions, but their truth conditions are the same as similar presumptions. Once the machinery of ad-hoc quantification is introduced, it turns out to be useful to model thought experiments, to study questions such as: What would be provable had ... been the case?

It is important to note that all three nonclassical quantifiers are introduced to deal with the fact that causal stories yield default rules. As long as exceptions are not dealt with, all three of them can be interpreted as universal quantifiers. Because the present paper is part of an exercise to rebuild the foundation of organizational ecology, we must be prepared for exceptions even if the exceptions do not show up here. We intend to build a module of a larger model, so compatibility has to be secured with the later additions. Use of the nonmonotonic logic gives the best chances for establishing such compatability.

About the Formal Logic

Causal stories refer to regularities in the world. We consider them to be true if the regularity is indeed present and to be false if the regularity they express is absent from the actual world. This makes their falsification and verification equally difficult, though not impossible. We use a model-theoretic approach to logic. We build models for the premises and use these models to identify the implications of the premises. If we know exactly which sentences are true, then we know how the world looks through the looking glass of the language. Premises that provide only partial information, therefore, cannot describe the world completely. Instead of telling how the world looks, they provide a description of several alternative pictures, one of which is the picture of the real world. In logic these alternative pictures are called *possible worlds*. To build a model for classical logic it is sufficient to refer to one possible world, the actual one. Intensional logics were introduced to study arguments that deal with several alternative possibilities.[15] Models for intensional logics are constructed from a set of possible worlds. The intension of a sentence is a function that tells its truth value in all possible worlds; we denote the intension of the sentence ϕ as $[\![\phi]\!]$.

A theory stage has two components, a set of possible worlds and a set of regularities. The first component captures the factual information: Only those possible worlds are in the set that satisfy the factual premises. The set of regularities[16] represents the established causal stories. Theory augmentations with ad-hoc assumptions are represented by theory stages made as similar to the not-augmented theory stage as possible while making the ad-hoc assumptions true.

Arguments are modeled by regularity chains. The linking condition for building a chain is that the antecedent of the second premise should be more general/less specific than the consequent of the first premise. To find out whether a theory stage implies a formula of the form

$$\mathfrak{P}[\phi \to \psi],$$

one should take the most-specific regularity chains that connect $[\![\phi]\!]$ to $[\![\psi]\!]$ and demonstrate that at least one of them is more specific than any regularity chain that connects $[\![\phi]\!]$ to $[\![\neg\psi]\!]$. In this paper we can restrict ourselves to the first half of the task because the arguments do not supply any regularity chains that connect $[\![\phi]\!]$ to $[\![\neg\psi]\!]$ in case of the theorems and lemmas we prove.

Endnotes

[1]Barnett and Carroll (1995) and Carroll and Hannan (2000) review the relevant research.

[2]The micro-units in ecological theory are organizations, not persons, and the macro-units are populations of organizations. Of course, one might strive for a theory that begins with persons and derives implications for organizations and populations. In our view, the current state of empirical and theoretical knowledge does not support such an ambitious approach. See Hannan (1992) for an extended discussion of these strategic issues.

[3]In terms of the formalisms of the theory-building strategy, this would work as follows. Suppose that $A(p)$ is a postulate of the theory. Then the theoretical claim formulated in a way that allows for accidental exceptions would be stated as $\mathfrak{N}p[A(p)]$. We do not introduce this level of complication in our formal rendering of the theory.

[4]In Simon's model, the core of the employment relationship is the notion that the employee will allow the employer to choose tasks from some restricted range of options.

[5]In formal terms, $\forall\, o, o', u[\mathsf{U}(u, o) \wedge \mathsf{U}(u, o') \to o = o']$.

[6]Bonacich's measure (in the original notation) is

$$\mathbf{c}(\alpha, \beta) = \alpha \sum_{k=0}^{\infty} \beta^k \mathbf{R}^{k+1} \boldsymbol{l}.$$

This version is tuned to allowing the importance of direct and indirect connections to vary in importance. In our context, we do not need to make this distinction. Thus, we have simplified Bonacich's measure by setting $\alpha = \beta = \pi_o$.

[7]We use the abbreviation A.x to refer to ad-hoc assumption x; similarly we use D.x for definitions, P.x for postulates, L.x for lemmas, and T.x for theorems.

[8]In the first case, some of the work of the first reorganization might need to be undone in the second, which would tend to lengthen the process. However, the second case involves a more highly constrained reorganization (because it deals with constraints coming from different sources). So there does not seem to be a strong argument that either would generally take longer.

[9]The *Oxford English Dictionary* defines intricate as "perplexingly entangled or involved; interwinding in a complicated manner."

[10]We make the standard assumption that two or more events cannot occur at the same instant.

[11]All of the lemmas and theorems would hold (in modified form due to the greater complexity of implementing this assumption) if we substituted this alternative ad-hoc assumption. Nonetheless, we want to make the ad-hoc assumptions as innocuous as possible. We want to show that the argument is sound even when we make the weaker assumption that every unit is equally likely to initiate a change.

[12]For the discrete case, the law of total probability states that

$$\Pr\{X \le x\} = \sum_y \Pr\{X \le x \mid Y = y\} \cdot \Pr\{Y = y\}.$$

[13]In formal terms,

$$\mathsf{RE}(u, t, t') \leftrightarrow \exists\, u', w[(v(u, u', w) = 1) \wedge (w \le t) \wedge (w + D(o, t) \mid \delta(u, t) = 1) > t')].$$

[14]The equality condition follows from the background assumption that the trichotomy relation holds, that if it is not the case that $a > b$ or $a < b$, then $a = b$.

[15]Gamut (1991) provides an accessible overview of developments in intensional logic.

[16]We model regularities by pairs of formula intensions: The first element in the pair is the antecedent in an implication and the second is the consequent.

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